

Perspectives of Stirling engines use for distributed generation in Brazil

Maria Eugenia Corria, Vladimir Melian Cobas, Electro Silva Lora*

Department of Mechanical Engineering, Federal University of Itajuba- UNIFEI, Ave. BPS 1303, Pinheirinho, Itajubá CEP 37500-903, MG, Brazil

Available online 29 August 2005

Abstract

This work presents an evaluation of the development of Stirling engines and the advantages and the main obstacles against their widespread introduction in energy-generation practices. It also shows how the economic, technical and environmental characteristics presented by these engines support their insertion in the energy sector. An economic and environmental evaluation of this technology aiming at introducing it in the Brazilian energy scenario is also presented. Changes in legislation, financing and technology within the next few years must encourage the implementation of alternative generation technologies that present lower environmental impacts. Also, tendencies and economical studies are presented, trying to find the optimal condition for this technology to be feasible. The option regarding the trading of carbon credits when biomass is used as fuel is analyzed as well.

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Stirling engine; Distributed generation; Biomass

1. Introduction

In 2002, Brazil has experienced maybe the most serious electric energy shortage of its history since the early 1950s. A 20% compulsory reduction in consumption, which lasted for 9 months, was imposed on the most populous regions of the country: the Southeast and the Northeast. The problem occurred because the generating park was not expanded to the necessary levels. This coincided with a summer that presented highly adverse hydrological conditions. The system, then, became vulnerable and could not meet the market's needs. The management of the energy crisis was conducted with considerable efficiency and with the consumers' full cooperation, who voluntarily replaced several pieces of equipment presenting high energy consumption for others that were more efficient. They also changed processes and habits in an attempt to reduce consumption. Moved by these problems and trying to reduce the dependence of the present electric

supply system on rainfall, the government decided to make changes in the energy model so as to assure its sustainable development. Aiming for this goal, several laws encouraging the use of alternative sources are being implemented. But this alone is not enough to lead to a robust technological paradigm approach in a country such as Brazil, where more than 90% of the electricity supplied by the energy matrix comes from hydroelectricity. In addition, the recovery of the water levels at the hydroelectric plants reservoirs to theoretically safe margins, only 1 year after the crisis, has caused these incentive policies to advance in a slower pace.

On the other hand, there is another problem that regards the electricity tariffs, whose values have ballooned substantially and must be inflated even more because of several factors: a higher marginal cost of the new generation capacity, currency devaluation, which has a significant influence on sectors that have many imported items and foreign capital, additional costs and loss of income as a result of the energy crisis.

Within this scenario, surrounded by uncertainties regarding supply and the electricity prices, several consumers, mainly the ones coming from the industrial and commercial sectors, have started to look towards

*Corresponding author. Tel.: +55 35 36291321;
fax: +55 35 36291355.

E-mail address: electo@unifei.edu.br (E. Silva).

other energetic supply alternatives, especially cogeneration, which can assure a much safer energy and, in many cases, is a much cheaper alternative.

These other alternatives, generally, refer to different technologies that are able to generate energy separately from the conventional electric grid presenting similar or even better quality and reliability. It is the so-called distributed power generation (DG).

DG is any small-scale electrical power generation technology that generates electric power at a site that is closer to customers than the central station generation and is usually interconnected to the distribution system or directly to the customer's facilities. Currently the world's distributed generation installed capacity is about 75 GW (ABI Research, 2003). According to Kreider and Curtiss (2000) and Thompson (2002), the distributed power is able to capture about 7–20% of the world's increase in generating capacity, or 55–110 GW, over the next two decades (Brown, 2003). Fig. 1 show the prognoses in relation to electricity coming from distributed generation in the period 2010–2030 based on data from the world energy outlook 2002 from IEA (Fraser, 2003).

DG technologies include small combustion turbine generators, internal combustion reciprocating engines and generators, photovoltaic panels, wind turbines, fuel cells and other technologies, including solar dishes and biomass-fuelled Stirling engines.

The purpose of this paper is to present an evaluation of the evolution and development of Stirling engines, as well as the advantages and main obstacles against their widespread introduction in energy generation practices. It will also show how the economic, technical and environmental characteristics of these engines support

their insertion in the energy sector. An economic and environmental evaluation of this technology aiming at introducing it in the Brazilian energy scenario is also presented.

2. The Stirling engine (SE)

The Stirling engine is an external combustion reciprocating engine developed by Robert Stirling in 1817. It uses an external source of energy to heat the gas located inside a cylinder. This gas, under pressure, expands when heated, driving a piston to perform work. The expanded gas volume, having released much of its energy, is then cooled and compressed before the next heating cycle.

The Stirling cycle engine is well suited for stationary power. It is inherently fuel-efficient—having a high theoretical efficiency among small capacity heat engines. And it is inherently “green”, for it can use different types of renewable sources of energy including solar and geothermal energy, biomass and biogas from animal waste and garbage. As it involves continuous burning of the fuel rather than the intermittent burning presented by internal combustion engines, it burns the fuel more completely, producing far lower unwanted emissions (Thompson, 2002; Mc Kenna, 2003).

Stirling engines constructions can be classified in three types: alpha, beta and gamma. The alpha-type engines consist of two-independent cylinders, placed in an angle of 90°, with two pistons. One of the cylinders is heated up and the other is cooled down through a finned transfer surface using air or water. Fig. 2 shows the cycle stages using engine schemes and a pressure/volume diagram. Fig. 3 shows an ideal cycle and a real cycle in a pressure/volume diagram.

The beta-type engine is based on Stirling's original engine. It consists of a cylinder with a hot zone and a cold zone. The displacer is inside the cylinder. The gamma-type engine is derived from the beta, but it is easier to build. It consists of two separate cylinders. The displacer is placed inside one of them and the power cylinder is inside the other. Fig. 4 displays an outline of each type of engine.

3. Attractiveness, obstacles and opportunities

Among the main advantages presented by Stirling engines

- Global efficiency of about 30%, which makes them competitive against other small capacity generation technologies. According to Carlsen et al. (1996) for a 40 kW Stirling engine, an increase in the heating gas

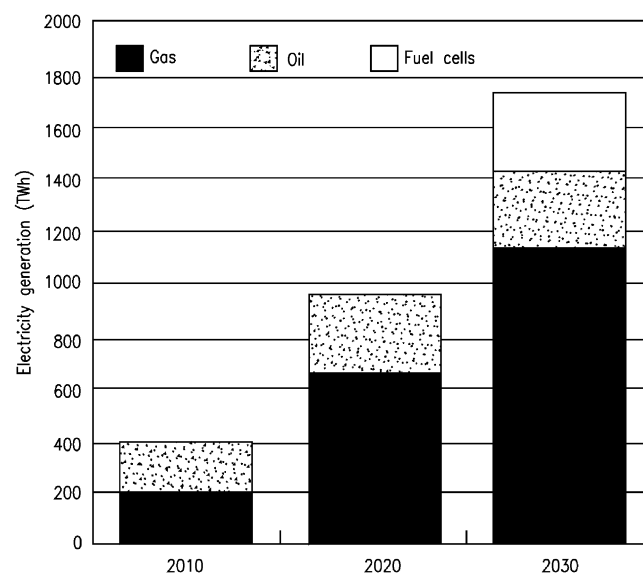


Fig. 1. Distributed energy technologies—electricity generation prognosis for 2010–2030 (Fraser, 2003).

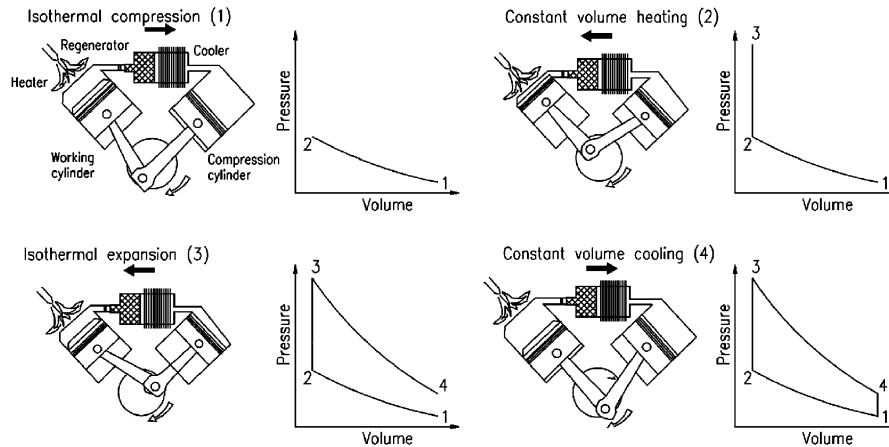


Fig. 2. Stirling engine operation principle.

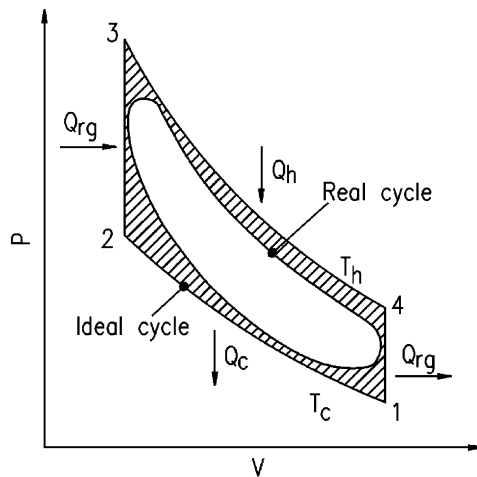


Fig. 3. Stirling engine ideal and real cycles.

temperature from 360 °C to 700 °C corresponds to a rise of 25% in efficiency;

- high efficiencies during partial load operation (SOLO Stirling Engine, 2002);
- low NO_x and CO emissions;
- safe operation and low level of noise;
- low maintenance cost. It was estimated to range about 0.008 US\$/kWh, much lower than typical values for internal combustion engines (0.020 US\$/kWh) (Mc Kenna, 2003);
- the possibility of using a wide variety of fuels;
- expected useful life of about 25 000 h (Jakobsen et al., 1998);
- possibility of cogeneration implementation.

The disadvantages that can be mentioned are:

- Capital costs of Stirling engines are relatively high, mainly because they are currently manufactured in very low quantities. Developers are working to lower

costs through a combination of design refinement and material substitution;

- few fuels have been tested. Problems may occur when residual fuels are used. Among them we can highlight: rust, tar and particles, which may reduce the efficiency of the heat exchanger. Tests have shown this type of difficulty with LPG and liquid fuels (Kreider and Curtiss, 2000);
- only small power engines have been tested (9–75 kWe). In the future, engines with 150–300 kWe must be designed and tested (Carlsen, 2004; Mc Kenna, 2003);
- data regarding reliability and useful life are scarce.

Despite the air pre-heating for combustion, the emission level is very low presenting only a few mg/m³ of NO_x and CO (NO_x emission depends on the maximum temperature and not on pre-heated temperature). Fig. 5 shows the values of the main pollutants emissions for Stirling engines compared with conventional heat/power combined units (CPH) (SOLO Stirling Engine, 2002).

The possibility of using biomass as fuel makes Stirling engines attractive for isolated regions where this resource is available and where the electricity supply through the grid is completely unfeasible. If they are compared with other energy alternatives that are commonly used in isolated areas (solar and wind energy, internal combustion engines) and other promising technologies (micro turbines, and fuel cells), biomass fuelled Stirling engines are still more attractive: they have a continuous and stable service, do not need other auxiliary generating sources and eliminate high costs associated with consumption and transport of fossil fuels. Coupling the engine with a biomass furnace or a biomass gasifier is also an option. In the first case the engine will use the energy from the hot combustion gases. A pilot plant designed and tested by the Technical

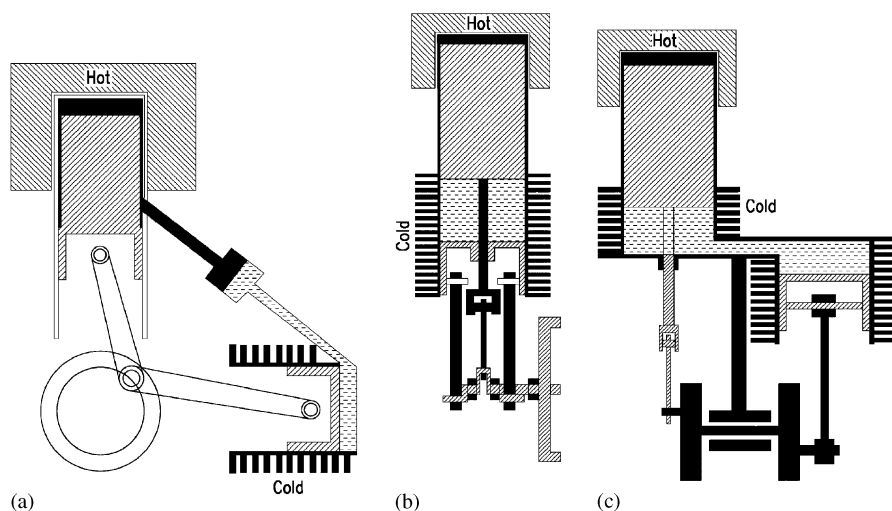


Fig. 4. Types of Stirling engines: (a) alpha, (b) beta, (c) gamma.

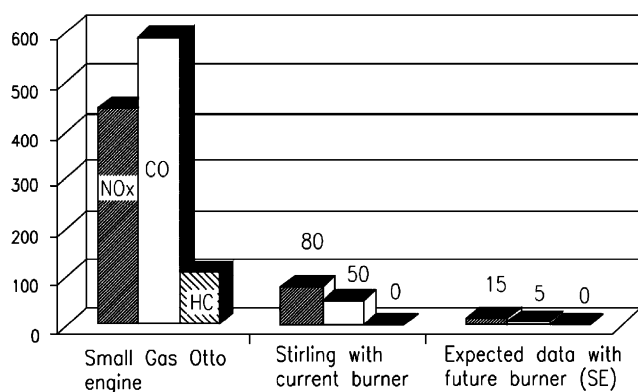


Fig. 5. Emission of NO_x, CO and HC from conventional and Stirling cogeneration units (mg/m³). Adapted from SOLO Stirling Engine (2002).

University of Denmark showed an electrical and overall efficiency of 19% and 87%, respectively, when burning 40% moisture biomass (Carlsen and Ammundsen, 1996). A Stirling engine/biomass updraft gasifier pilot plant was tested in Denmark, showing an efficiency of 0.153%, and its great advantage is a low intensity of ash deposition in the heat-transfer surface of the engine (Carlsen et al., 2002). Both the technological options are being currently tested at the laboratories of the Federal University of Itajubá-UNIFEI (Minas Gerais, Brazil).

In Brazil, the electricity supply to isolated regions has been a serious problem and lacks a short-term solution. A considerable part of the electricity consumed in these regions, produced by using fossil fuels, is subsidized by the government by sharing this cost among all the consumers of the country. The value of the subsidies for the use of fossil fuels for electricity generation in Brazil in 2005 should be about 108 million a month (Canal Energia, 2005).

The Brazilian energy legislation establishes incentives to reduce the use of fossil fuels in isolated regions

without affecting their economic development. This incentive policy offers for the generating plants using alternative sources of energy, mainly biomass, the same subsidies it offers for the ones using diesel. PROINFA (a program to encourage the use of alternative sources of energy) encourages the use of renewable sources and assures the purchase of this energy for 15 years (EM, 2004). The main goal of this program is for the Brazilian energy matrix to produce 10% of its power out of renewable sources within a period of 20 years.

The use of biomass for electricity generation may perform a very important role in the near future because of the advantages granted by the clean development mechanism (CDM), which is a necessary contribution towards the reduction of CO₂ emission levels established by the Kyoto Protocol. Approximately between 8% and 12% of the investments in CDM are forecast to be channelled to Latin America representing 3.670 billion tons of reduced CO₂ in the period between 2008 and 2012 (CEDBS, 2002). This will take place due to the fact that industrialized countries are unable to reduce their carbon emissions in the short term and the less industrialized countries need to develop.

The possibility of trading carbon credits (carbon emissions that were avoided by using clean technologies)—today estimated in the range of US\$ 3.40 and US\$ 7.50 per ton of carbon dioxide in the future—must greatly contribute towards the feasibility of these kinds of project.

In relation to biomass, the only commercial technologies available are the steam cycle and the steam engine characterized by their low efficiency. The gasification technology using biomass gasifier/diesel engines sets has not been greatly spread because of operational difficulties and high investment costs. Technologies including micro turbines and fuel cells using biomass gasification are undergoing their initial phase of development. Thus,

the Stirling engine presents itself as a promising technology as far as the use of biomass is concerned.

It is possible to conclude that within its technological and political scenario, Brazil is prepared to use Stirling engines in meeting the needs of isolated regions.

4. Economic evaluation

In order to carry out the economic analysis, a range of real prices of Stirling engines available at the market in a pre-commercial phase were used. Considered manufacturers were SOLO (Germany) and STM (USA). This study intends to look for the optimal scenario where the Stirling engine can be economically feasible when compared to the electricity purchased from the grid, which is approximately 100 US\$/kMWh (Table 1).

A more detailed study about the price of the electricity consumed in Brazil's isolated regions must take the generation cost at diesel plants into account, which is much higher than the average cost in the Brazilian interconnected system, because it is mainly based on water resources and has no fuel costs. The reference for this analysis will be the cost of energy purchased from the grid considering that the price paid for electricity services in isolated areas is similar to the rest of the interconnected system, as previously explained.

This paper analyzes a scenario including an Independent Electricity Generator, who does not intend to commercialize the generated energy, but to avoid the purchase of electricity at the average tariffs charged in isolated systems. That is the reason why the generation cost of the Stirling engine is compared with the system electricity tariff.

The economic evaluation also carried out a sensitivity analysis by varying the price of biomass, the price of the engine and by using the two baselines referred to CO₂ emission level (the upper and lower bounds) for the Brazilian isolated electric system (Esparta and Martins, 2002), based on the installed capacity in 1999. These

baselines are expressed in tons of carbon, which is the amount that a generation project using fossil fuel would produce. By replacing this kind of generating plant for one using a renewable source, its emissions would be completely eliminated and that would represent a gain in Certificate of Reduced Emission (CERs) or carbon credits.

The CERs can contribute significantly towards the reduction of the generation cost of any generation project using renewable sources.

The main economic parameters and costs used for the analysis are shown in Table 2. Biomass gasifier and cleaning system cost were taken from data of a real prototype that was installed and is being tested at UNIFEI's laboratories. System efficiency and fuel consumption were obtained as a result of design calculations.

5. Result analysis

One of the main obstacles for the widespread use of advanced technologies for electricity generation is the investment cost. This is also valid for the Stirling engine

Table 2
Main parameters used for the calculations

SE electrical power (kW)	200
Fuel consumption (ton/day)	4.4
System efficiency (%)	30
SE cost range (US\$/kW) ^a	1125–3000
Gasifier system installed (US\$)	60 000
Other costs (US\$)	145 200
Average cost of system (US\$)	511 200
Specific cost of system range (US\$/kW)	2556–4356
Interest rate (%)	15
Range of price of CERs (US\$/ton CO ₂)	3.4–7.5
Upper bounds baseline (isolate systems) (kg °C/MWh)	243.7
Lower bounds baseline (isolate systems) (kg °C/MWh)	174.7
SE useful life (years)	15
Capacity factor (%)	90

^aSTM Power Corporation and SOLO.

Table 1
200–300 kW engine comparisons (Stirling Advantages Inc., 2000)

	Stirling	Reciprocating	Microturbine ^a	Fuel cell
Installed capital cost (kW)	\$1125–\$3000	\$500–\$900	\$1.350	\$3.350
Electrical efficiency (%)	30	34	26	32–50
NO _x emissions (kg/MWh) ^b	0.22 ^c	9.88	0.52 ^d	0.004
Electricity cost/kWh	\$0.070–\$0.090 ^e	\$0.085	\$0.108–\$0.150	\$0.150–\$0.200

^aData from Capstone 30 kW and Honeywell 75 kW units.

^bData from Weston et al. (2001).

^cData from Mc Kenna (2003).

^dData measured at NEST/UNIFEI laboratories using natural gas as fuel (Gomes, 2002).

^eEconomic feasibility study results from Podesser (2000).

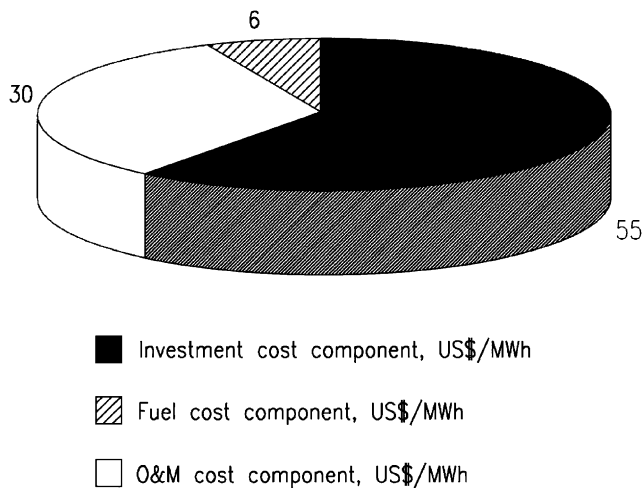


Fig. 6. Generation cost components.

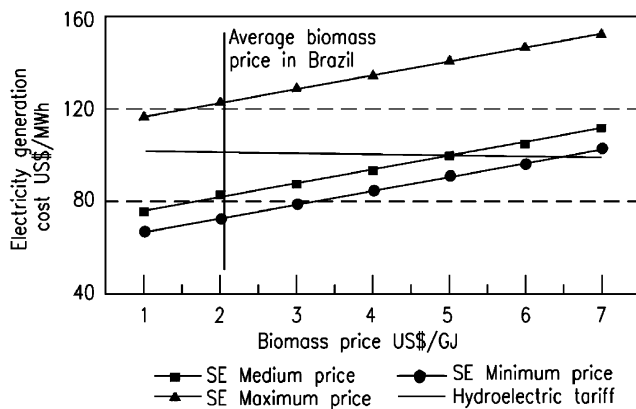


Fig. 7. Relation between the generation cost and the biomass price for different SE prices.

as new technology in the market. Fig. 6 shows the weight of the investment in the generation cost with Stirling engines.

Fig. 7 shows the relation between the generation costs with biomass Stirling engines for different engine cost scenarios and biomass market prices. This graph considers three engine cost levels (maximum, medium and minimum) for Stirling engines. The influence of the cost on the economic feasibility of the project is enormous, but for Stirling engines with prices ranging between 1125 and 1500 US\$/kW (minimum and medium) the generation cost may be lower than the cost of the electricity purchased from the grid in the Brazilian interconnected system. The generation cost will only surpass the tariff that is charged today if the price of biomass is too high.

This result shows the feasibility of using this technology not only in accordance with today's conditions, but also in the near future. It is important to highlight the logical downward trend in relation to the prices of Stirling engines, for this technology is still

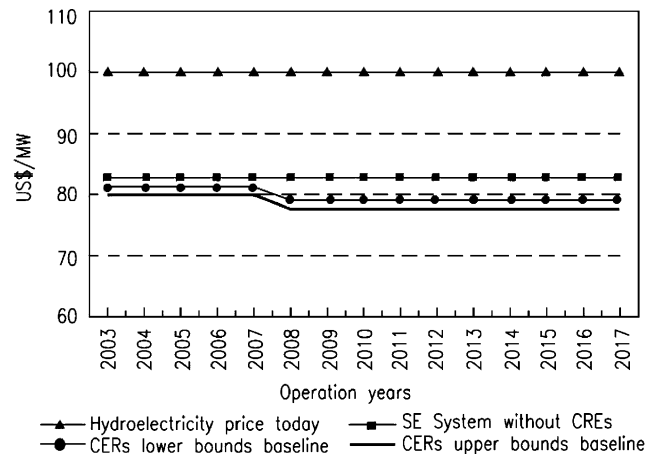


Fig. 8. Relation between the SE generation cost at different conditions and the hydroelectricity present market price.

being developed and it is undergoing the initial phase of market participation penetration.

Fig. 8 shows the influence that the CERs can have on the generation cost. In this case, it is assumed that a certain Annex 1 country, which belongs to Kyoto's Protocol Attachment I, subsidizes a CDM project selling the clean technology of which CERs are already discounted from the initial investment cost. This figure compares two baselines: maximum and minimum. It also considers two prices per tons of avoided carbon (3.4 and 7.5 US\$/tonCO₂) as expected before and after 2008, respectively, which is the year when the countries that are part of Annex I must start reducing their emissions. It is also possible to observe that the influence of the CERs price variations on the generation cost is a lot more significant than the baseline level determination. The price of the Stirling engine used for this analysis is the average price of the range shown in Table 2.

6. Conclusions

The Stirling engine has met the economic and technical conditions to become one of the most promising technologies used for electricity generation. By analyzing the factors associated with the generation cost, the investment presents a considerable specific weight, but the technological development and large-scale commercialization may reduce this cost. The increase in biomass prices in the future may not affect the feasibility of energy enterprises using Stirling engines, which assures its use in the long run. Today, there are Stirling engines in the market that are widely competitive against the average tariff of the Brazilian interconnected system. That could make their use viable, not only in isolated systems, but in the interconnected system as well. Regarding the latter, other advantages

can also be considered, such as the reduction of losses and costs with new power lines and the possibility of using municipal solid waste (MSW), which constitutes a problem in large cities. Future studies that will be carried out by our research group aim at the possibility of implementing a pilot plant using Stirling engines in an isolated area of the country.

References

- ABI Research, 2003. Distributed Generation. Growth Forecasts for Fuel Cells, Photovoltaics, Wind Turbines, Reciprocating Engines, and Small Gas Turbines.
- Canal Energia, 2005. Aneel fixa valores da CCC para 2005, 27/1/2005, www.canalenergia.com.br.
- Carlsen, H., 2004. Stirling engines for biomass fuels. Status and prospects of small-scale power production based on Stirling Engines—Danish Experiences. <http://www.nord.planergi.dk/stirling2.htm>.
- Carlsen, H., Ammundsen, N., Traerup, J., 1996. 40 kW Stirling engine for solid fuels. Proceedings of the European Stirling Forum 1996, vol. 1. Osnabrück, Germany, pp. 139–146.
- Carlsen, H., Bovin, J.K., Werling, J., Jensen, N., Kittelmann, J.F., 2002. Results from tests of a Stirling engine and wood chips gasifier plant. Proceedings of the European Stirling Forum 2002, CD. Osnabrück, Germany.
- Fraser, P., 2003. DG within Liberalized Electricity Markets and Prospects to 2030. COSPP, vol. 4(1). pp. 31–40.
- Gomes, E.E.B., 2002. Análise técnico-econômica e experimental de Microturbinas a gás operando com gás natural e óleo diesel. Ph.D Thesis, Federal University of Itajubá.
- Jakobsen, H.H., Houmoller, S., Pedersen, L.T., 1998. Technologies for Small Scale Wood-fuelled Combined Heat and Power Systems, Dk-TEKNIK. Soborg, Denmark, 61p.
- Kreider, J.F., Curtiss, P.S., 2000. Distributed Electrical Generation Technologies and Methods for their Economic Assessment. ASHRAE Transactions 2000, vol. 106. Atlanta, USA.
- Mc Kenna, J., 2003. Game changer: Stirling engines at landfills, Landfill Methane Outreach Program. 6th Annual Conference and Project Expo.
- EM, 2004. Governo lança PROINFA mais paga menos pelo MWh, Eletricidade Moderna, No. 361, pp. 20, 22.
- Podesser, E., 2000. Electricity production in rural areas with a biomass Stirling engine. In: 2000 International Environment and Renewable Energy Conference, Beijing, China.
- SOLO Stirling Engine, 2002. Technical Documentacion. CD. Best.No: 990416102. Sindelfingen, Germany.
- Stirling Advantages Inc., 2000. www.stirlingadvantage.com apud PowerGen. OR, USA.
- Thompson, J., 2002. Does Size Really Matter? Distributed Power and its impact on Centralized Power Generation Plants. COSPP Review Issue, vol 3(4). pp. 41–53.
- Weston, F., Seidman, N.L., James, C., 2001. Model regulations for the output of specified air emissions from smaller-scale electric generation resources. The Regulatory Assistance Project, www.raponline.org.

Further reading

- Conselho Empresarial Brasileiro para o Desenvolvimento Sustentável (CEBDS), 2002. Mercado de Carbono. www.cebdes.com.
- Esparta, A.R.J., Martins, C.M., 2002. Brazilian Greenhouse Gases Emission Baselines from Electricity Generation. Ecoinvest Assessoria Ltd., SP.
- STM Power Corporation and SOLO, 2002. Personal communication.